Impact of mountains on tropical circulation in two Earth System Models

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Abstract

Two state-of-the-art Earth System Models (ESMs) were used in an idealized experiment to explore the role of mountains in shaping Earth's climate system. Similar to previous studies, removing mountains from both ESMs results in the winds becoming stronger and more zonal, and weaker Indian and Asian monsoon circulations. However, there are also broad changes to the Walker circulation and the El Niño Southern Oscillation (ENSO). Without orography convection is unmoored from the Maritime continent, crossing the entire Indo-Pacific basin on interannual timescales. The ENSO has a stronger amplitude, lower frequency and increased regularity. A wider equatorial wind zone and changes to equatorial wind stress curl result in a colder cold tongue and a steeper equatorial thermocline across the Pacific basin during La Niña years. Anomalies associated with ENSO warm events are larger without mountains, and have greater impact on the mean tropical climate than when mountains are present. The mean Pacific Walker circulation weakens in both models by ~45%, but the strength of the mean Hadley circulation changes by ~2%. Unlike in studies examining the influence of radiative forcing on atmospheric circulation, changes in the Walker circulation in these experiments are not driven by changes to surface temperatures and the hydrologic cycle, but are explained by the large spatial variance in circulation on interannual timescales. These results suggest that mountains are an important controlling factor in large-scale tropical circulation, impacting ENSO dynamics and the Walker circulation, but have little effect on the strength of the Hadley circulation.

1. Introduction

Land-surface topography is a fundamental boundary condition of Earth's climate system. As such, there is a >40 year history of numerical modeling experiments that examine the role of orography in shaping broad features of the climate system. Authors have used a paleo approach in which orographic height and location correspond to best estimates of continental configurations and orography from specific periods in Earth's history (e.g. Barron and Washington 1984); a regional approach, in which the height of specific orography is varied (Xu et al. 2004; Takahashi and Battisti 2007; Insel et al. 2009; Boos and Kuang 2010; Feng and Poulsen 2014; Maroon et al. 2015); and a global approach, in which the height of all of Earth's land-surface topography is varied systematically (e.g. Manabe and Terpstra 1974; Kutzbach and Guetter 1989; Kutzbach et al. 1993; Manabe and Broccoli 1990; Kitoh 1997, 2004; Abe et al. 2004; Kitoh 2007).

Early idealized studies that varied global orography in general circulation models were limited by computing resources, and therefore carried out relatively short simulations using simplified models (e.g. atmosphere-land models with no ocean component) and focused their analysis on mid-latitude climates where the influence of mountains on standing atmospheric waves is strong (Manabe and Terpstra 1974). Similar studies were repeated over the following three decades as models improved in terms of their resolution in space and time, included more components of the climate system (e.g. the ocean, cryosphere, and land vegetation), and refined the physics related to sub-grid parameterizations (Kutzbach et al. 1993; Kitoh 1997, 2002). Of these studies, only simulations run in the early 2000s used a fully coupled atmosphere-ocean general circulation model (AOGCM) without flux adjustments. Although these simulations, integrated for fifty model years, represented a significant advance in global climate models at the time, today's state-of-the-art Earth System Models (ESMs) boast improved parameterizations, a higher component coupling frequency, and higher spatial resolutions that better resolve topographic details and improve the land-sea mask. Due to increased computing capacity ESMs are commonly integrated for hundreds to thousands of model years, whereas earlier AOGCMs were typically integrated for tens of model years.

In this paper, we present the results of an idealized experiment in which we adopted the global approach to varying Earth's land-surface topography in order to better understand the influence of mountains, at the largest scale, on the climate system. We removed all land-surface topography from two state-of-the-art ESMs and ran our simulations for over 500 model years. Previous work had found that removing orography causes mid-latitude westerly winds to become more zonal (e.g. Manabe and Terpstra 1974), monsoon circulation to weaken (e.g. Kitoh 2004; Lee et al. 2015), and global surface temperatures to rise by 1-1.5°C (Barron 1985; Kutzbach et al. 1993; Kitoh 1997). ENSO was reported to become more regular with a higher amplitude and lower frequency without mountains (Kitoh 2007). However, due to the relatively short integration, it was unclear if that result would be found in a longer experiment. With this caveat, we expected that our ESMs would give similar results to previous experiments, and would allow us to diagnose changes to the climate system to an unprecedented degree. The increased model resolution and complexity of the model were expected to provide potentially new results. We were encouraged by the fact that these ESMs and their predecessor simulate ENSO very well (Wittenberg et al. 2006; Guilyardi 2006;

Guilyardi et al. 2012). Additionally, these experiments would allow us to examine the role of orography in producing model biases such as the too-warm ocean current off the coast of Peru associated with the coarse representation of the Andes (Philander et al. 1996; Wittenberg et al. 2006).

Although our results are broadly consistent with previous studies, the impact of mountains on tropical climate was much more profound than we expected. The changes observed in our simulations suggest that mountains play a primary role in shaping tropical climate through their impact on ENSO and the Walker circulation. The results are exciting from a climate dynamics perspective because ENSO has a strong influence on global climate on interannual timescales. They will also be of interest to the paleoclimate community because changes to ENSO and the Walker circulation are considered to play an important role in the Earth's slide into the so-called icehouse climate since the Pliocene (Ravelo et al. 2004; Fedorov et al. 2006; Brierley and Fedorov 2010; Fedorov et al. 2013), and links between the progressive aridification of the East African rift region since the late Miocene and hominin evolution have been the subject of research for well over a century (see Domínguez-Rodrigo 2014 for a recent review).

In the next section we describe the models and observation-based data used in this study. Section 3 examines the mean tropical circulation in the PANCAKE simulations, and Section 4 explores the interannual variability. Section 5 is an analysis of the influence of ENSO on the mean circulation, and Section 6 presents an analysis of the mechanisms driving the changes to ENSO. Our conclusions are reported in Section 7.

2. Data and models

We removed land-surface topography, including ice height, from two GFDL ESMs, ESM2Mb and ESM2G, which differ only in their oceanic components (ESM2Mb uses a depth-based vertical coordinate, z*, whereas ESM2G uses an isopycnal vertical coordinate) and have identical atmosphere, ice and land surface components (Dunne et al. 2012, 2013). These models resolve the diurnal cycle, using a 30 minute time step for atmospheric variables, a one hour time step for oceanic variables and coupling between model components, and a 3 hour radiation time step (Dunne et al. 2012, 2013). The ESM2Mb model is very similar to the GFDL ESM2M except the above-ground land biomass was adjusted to better match ESM2G and observations (Dunne et al. 2012, 2013). The physical climate and response to changes in forcing are very similar between ESM2M and ESM2Mb. Figure S1 compares Earth's observed topography (etopo120) with our CONTROL topography and Figure 1 compares the CONTROL topography with that from our experiments with the mountains removed, which we refer to as PANCAKE. In PANCAKE, we did not change river routings, the geographic distribution of albedo associated with high latitude glaciers (i.e. Antarctica and Greenland are white in PANCAKE, assuming an ice-sheet-covered surface, but the topography associated with glaciers was removed), ocean bathymetry, or sea-level (ice removed from continents was not added to the ocean). Consistent with flattening model topography, the topographic momentum drag scaling scheme and the gravity wave drag scheme were both turned off in PANCAKE. The CONTROL experiments were run with pre-industrial radiative forcing and atmospheric chemistry.

The PANCAKE experiment was run in both ESM2Mb and ESM2G for over 500 model years, and years 401-500 are used throughout this analysis to represent the semiequilibrium climate state, defined here as having a net radiative imbalance at the top of the atmosphere of less than 0.75 W/m^2 (Figure S2). Throughout this paper we compare our CONTROL climatological mean diagnostics with the European Centre for Medium-range Weather Forecasts (ECMWF) ERA-INTERIM reanalysis product (Dee et al. 2011). For comparison with long time-series of ENSO-related variables, we use ECMWF's ERA-20c product (Compo et al. 2011). The CONTROL runs for both models and GFDL's closely related CM2.1 model have been reported to reproduce the broad features of the earth's climate system, and the two models tend to straddle observations (Guilyardi 2006; Wittenberg et al. 2006; Dunne et al. 2012; Kim and Yu 2012; Dunne et al. 2013; Bellenger et al. 2014). Figure S3 compares 100-year mean CONTROL tropical precipitation, pressure velocities (ω) and sea-surface temperatures with ERA-INTERIM climatological averages for those variables from 1981-2010. Both models exhibit well-known biases in tropical precipitation that are common to coupled climate models including too little rain over the Amazon region and a double ITCZ characterized by too much rain in the southern hemisphere over the central and eastern tropical Pacific (Dai 2006; Wittenberg et al. 2006; Dunne et al. 2012). Detailed analysis of the convective schemes used in our models and precipitation biases on diurnal to interannual time scales were performed on GFDL's CM2.1 model (Dai 2006; Lin et al. 2006).

The two Earth System Models used in this study produced the same qualitative results when the land-surface orography was removed. We focus our presentation below on the ESM2Mb results.

3. Mean circulation

Similar to previous studies (Manabe and Terpstra 1974; Ruddiman and Kutzbach 1989), Earth's winds are much more zonal when land-surface topography is removed (not shown). Changes to the strength of the global water cycle (both precipitation and evaporation) are less than 1% in both models, and the globally averaged surface air temperatures also exhibit small changes (PANCAKE is 0.67°C warmer in ESM2Mb and 0.23°C warmer in ESM2G), consistent in sign with previous studies but smaller in magnitude (Barron 1985; Kutzbach et al. 1993; Kitoh 1997). Average tropical (30°S-30°N) surface air temperatures also exhibit small changes (0.37°C in ESM2Mb and 0.25°C in ESM2G). However, the spatial pattern of tropical rainfall changes significantly in both experiments (Figure 2, Figure S4). Where tropical precipitation is high (low) in CONTROL, precipitation decreases (increases) in PANCAKE. Tropical precipitation is less focused in PANCAKE, where the maximum spreads out in both the meridional and zonal directions. The inter-tropical convergence zone (ITCZ) in the southern hemisphere is more developed in PANCAKE, extending farther across the Pacific basin than in CONTROL. Given the "double-ITCZ" bias in our CONTROL models, this tendency in the PANCAKE simulations is difficult to interpret, but is consistent with the fact that surface air temperature changes are larger in the southern hemisphere than changes in the northern hemisphere in both models. In PANCAKE, precipitation decreases most dramatically over the Maritime continent (~100°E-150°E), and increases over east Africa, the central equatorial Pacific (between ~180°-110°W), and most of the Amazon basin. Precipitation over India and Southeast Asia decreases, consistent with a weakened monsoon circulation. The changes to the spatial distribution of precipitation occur throughout the entirety of the tropics, including the central Pacific Ocean, and are not confined to regions of significant orography.

The changes to the spatial pattern of tropical rainfall are very similar to changes in ω in the middle of the troposphere (at 500 mbar, Figure 2). Where air rises very quickly (slowly) in CONTROL, it rises more slowly (quickly) in PANCAKE. The few exceptions to this relationship are in regions of significant topography (the central Andes, the Himalayas and the Sierra Madre). However, these areas constitute a small proportion of the tropics, and the differences are associated with local effects of removing topography. Apart from these local effects, there is clearly a broader impact; removing orography changes the location and strength of vertical air motion far away from the location of the orography, for example in the middle of the Pacific Ocean.

Tropical sea-surface temperatures (SSTs) decrease slightly in both experiments (-0.24°C in ESM2Mb and -0.25°C in ESM2G), as do global SSTs (-0.46°C in ESM2Mb and -0.43°C in ESM2G). The spatial pattern of SST changes (Figure 2, Figure S4) is distinct from the precipitation and ω anomaly patterns. For example, surface waters cool significantly to the east and west of the Maritime continent but are unchanged or warmer in the vicinity of the continent, whereas precipitation and ω decrease throughout this entire area. Precipitation and ω increase over a large region of the central equatorial Pacific, between 180° and 100°W, whereas SSTs decrease throughout that region.

Some of the largest changes in SST occur in the Peru current off the west coast of South America where PANCAKE's SSTs are ~5°C cooler than in CONTROL (Figure 2, Figure S4). This indicates that the coarse representation of the Andes in our CONTROL simulations is not the cause of the warm bias in the Peru current (Wittenberg et al. 2006).

The Walker circulation can be depicted as the average of ω over the equatorial tropics (5°S-5°N) in longitudinal-height space (Figure 3). The Walker circulation in the ERA-INTERIM reanalysis data (Dee et al. 2011) from 1981-2010 (Figure 3a) shows that the maximum velocities in the "up" direction (negative ω values) occur in the region of the Maritime continent, including the warm pool of the western Pacific and eastern Indian oceans, with significant upward motion over the longitudes of the Amazon rainforest. Air tends to descend over the eastern Pacific and Atlantic basins, and over east Africa. This overall pattern and the zonal variation in ω are reproduced by the CONTROL experiments (Figures 3, S5). Biases in the CONTROL simulation's Walker circulation include too concentrated upward motion over the Maritime continent and too little upward motion over the Amazon. In PANCAKE (Figures 3, S5), the zonal variation in ω is remarkably dampened. Although air tends to descend over the Atlantic region with the same intensity as in CONTROL, and the weak ω in the middle-of-the-troposphere over the central Pacific in CONTROL does not change much, the rest of the tropics have substantially reduced upward and downward vertical motions throughout the atmosphere.

Various metrics have been used as a measure of the overall strength of the time-mean Walker circulation, including the difference in sea-level pressure between the equatorial western and eastern Pacific (dSLP) (Walker and Chaiken 1932; Vecchi et al. 2006; Vecchi and Soden 2007), the maximum values of mass streamfunctions (Trenberth et al. 2000), and deviations from the zonal mean of ω in the middle of the tropical troposphere (Burls and Fedorov 2014). Each of these metrics calculated for the PANCAKE experiments exhibit a weakening of the Walker circulation in the range of

31-60% (Figure S6-S8, Table S1), with a mean value of 43% (ESM2Mb) and 45% (ESM2G).

Simulations from the second phase of the Paleoclimate Modeling Intercomparison Project (PMIP2), in which coupled GCMs were forced with last glacial maximum (LGM) conditions and double pre-industrial atmospheric CO2 concentrations (2xCO2), also show hydrologic-driven changes to the Walker circulation (DiNezio et al. 2011). These experiments exhibit a weakening (strengthening) of the tropical overturning circulation associated with warmer (colder) than modern global surface temperatures, which occurs preferentially in the Walker component of tropical convection (DiNezio et al. 2011).

Changes in PANCAKE tropical surface temperatures, water vapor content, precipitation and estimated convective mass flux are of a much smaller magnitude than those changes in the PMIP2 simulations (Figure 4). However, the Walker circulation weakens significantly more in the PANCAKE experiments than in any of the CO2-doubling simulations, and the magnitude of weakening in PANCAKE is similar to the magnitude of strengthening exhibited by the most sensitive LGM models (Figure 4). The magnitude of change to the total average upward component of ω in the middle of the troposphere (500mb) is greater in the PANCAKE experiments than the CO2-doubling and LGM experiments. The large change in ω compared to the very small changes to the global average surface temperature and the hydrologic cycle in the PANCAKE experiments indicates that feedbacks related to changes to the average surface temperature and the hydrologic cycle are not responsible for the broad tropical circulation changes seen in the PANCAKE results.

In a recent study the Andes were flattened in simulations using the National Center for Atmospheric Research's Community Climate System Model version 4 (Feng and Poulsen 2014), and the Walker circulation decreased by about ~22% compared with the control run that used modern Andes topography. The authors attributed this change to a 0.8°C decrease in the equatorial Pacific SST gradient when the Andes were lowered, associated with decreased low cloud formation over the southeastern Pacific basin. In our experiment removing orography decreased low cloud formation in the southeastern Pacific basin (not shown), but the equatorial Pacific SST gradient did not decrease as much (0.5°C in ESM2Mb and 0.3°C in ESM2G, Table S2) and the Walker decreased by about twice as much.

In addition to the overall weakening of the Walker circulation, the structure of the circulation is changed in the PANCAKE experiments. Air almost ceases to descend throughout most of the atmosphere over the western Indian Ocean and east Africa in the PANCAKE experiments (~35°E-55°E), disrupting the Indian branch of the Walker Cell. The upward branch of the Walker circulation in PANCAKE is not focused over the Pacific warm pool; it extends over the entire Indian Ocean.

The weakening of the Walker circulation in these experiments occurs without significant weakening of the Hadley circulation, which describes the zonally symmetric component of tropical convection. The Hadley circulation can be depicted as the zonal average of ω over the tropics (30°S-30°N) in latitudinal-height space (Figure 3). In ERA-INTERIM reanalysis data from 1981-2010 (Figure 3b), the average Hadley circulation is shown to be dominated by air rising in the northern hemisphere, consistent with the fact that the inter-tropical convergence zone (ITCZ) spends more time each year in the northern hemisphere. In the PANCAKE experiment, the large-scale ω pattern is even more symmetric around the equator, consistent with the spatial pattern of precipitation in Figure 2 and the greater increase in surface air temperature in the southern hemisphere compared with the northern hemisphere (Broccoli et al. 2006). This results in a sharper division between the equatorial region of low ω and the regions centered at about 7°N/S of the equator of high ω, due principally to diminished rains over the equator Maritime continent. The overall variation in the magnitude of average ω across different latitudes remains largely unchanged in PANCAKE, as does the overall width and height of the tropics. Based on the fractional change to the maximum value of the zonally-averaged overturning streamfunction between 30°S-30°N, the strength of the Hadley circulation changes are small (<2%) in the ESM2Mb and ESM2G PANCAKE experiments (Table S1).

4. Interannual variability

Although the pre-industrial CONROL simulations of the two models used in this study exhibit ENSOs with different characteristics, with ESM2Mb's ENSO stronger and ESM2G's ENSO weaker than observations (Kim and Yu 2012; Bellenger et al. 2014), the ENSO in both models changes in the same qualitative manner when mountains are removed. Without orography, the ENSO is characterized by larger amplitude, lower frequency and is more regular (Figure 5, Figure 6 a and b). ENSO's frequency, calculated from model years 101-500, changes from 3.7 to 5.7 years in ESM2Mb, and 2.8 to 4.9 years in ESM2G (Figure 5). The semiannual cycle in the Nino3 region (150°W-90°W, 5°S-5°N) is stronger in PANCAKE (Figure 5), especially in ESM2G, consistent with the increased meridional symmetry about the equator (see the Hadley Circulation in Figure 3d). Interannual variation in anomalies of equatorial SSTs, wind stress and precipitation in the Pacific and Indian basins increases in PANCAKE relative to CONTROL (Figure 7 a, b and c). In CONTROL and in observations, interannual anomalies extend across the Pacific basin in some years, but only reach the central Pacific in other years (Figure 7). In PANCAKE, they consistently extend across the entire Pacific basin (Figure 7). The increased strength of the ENSO in these experiments impacts the total tropical precipitation and global net radiation at the top-of-the-atmosphere (Figure 6 c and d).

Because these models share the same atmospheric component, similar experiments could be carried out with other fully coupled AOGCMs in order to test the robustness of this response. However, the qualitative consistency of the results between our two ESMs as well as a previous study (Kitoh 2007) is encouraging and suggests that these results are robust.

5. Influence of ENSO on the mean circulation

The response of the ENSO when orography is removed from these models is so strong that ENSO events have a much more significant influence on the mean climate in PANCAKE than they do in CONTROL. For example, in the CONTROL runs, as in nature, the distribution of monthly wind stress and SST anomalies over the Nino4 (160°E-150°W, 5°S-5°N) and Nino3 (150°W-90°W, 5°S-5°N) regions is nearly normal (Figure S9). Most months show no anomaly in these values, so the distribution peaks at the zero-anomaly line, and there is a very small tail with positive (westerly) wind-stress values and SSTs from ENSO warm events (Figure S9). Consistent with previous studies

(Kim and Yu 2012; Bellenger et al. 2014), ESM2Mb has a larger El Niño-related tail than the reanalysis data, whereas ESM2G's is smaller. In the PANCAKE simulations these distributions are different. Most common anomalies no longer fall on the zero-anomaly line, which is in-between La Niña and El Niño values (Figures 8, S9). Because changes to ENSO are often diagnosed through analysis of the mean climate, the strong impact of ENSO on the mean climate in the experiments complicates the interpretation of the results.

In order to distinguish aspects of the changes to the mean tropical circulation that are related to ENSO versus those that are not, and to diagnose the changes to ENSO, we compare the mean climate and circulation patterns from ten El Niño years and ten La Niña years in CONTROL and PANCAKE. Using time-series from model years 401-500, we picked spans of twelve months with consistent Southern Oscillation Index (SOI) and Nino3 SST anomalies, and repeated this process with the ERA-20c reanalysis (Figure 6). The Walker Circulation varies significantly between La Niña and El Niño years in the reanalysis; the ESM2Mb CONTROL simulation's circulation varies a little more than ERA-20c, and ESM2G's CONTROL exhibits more subdued variation (Figure S10), consistent with previous studies (Kim and Yu 2012; Bellenger et al. 2014).

PANCAKE's much stronger ENSO is apparent when comparing La Niña and El Niño years with CONTROL (Figure 9). In both ESM2Mb and ESM2G, the PANCAKE La Niña and El Niño years exhibit vertical velocities of similar magnitudes to CONTROL; however, the spatial pattern of upward and downward movement is different. During La Niña years, the region of descending air (red color in Figure 9 middle row) over the central and east Pacific extends ~20° farther west in PANCAKE; air descends over the eastern part of Indonesia. The descending air that is over East Africa in CONTROL also shifts west and is over West Africa and the eastern Atlantic in PANCAKE. During El Niño years, the large region of rising air over the Pacific (blue color in Figure 9 bottom row) shifts farther east, consistent with the increased longitudinal span of the anomalies shown in Figure 7. Air descends over most of the Indian Ocean, but not East Africa, and there is less rain over Indonesia. Although the equatorial circulation strength does not change much between CONTROL and PANCAKE during La Niña and El Niño years, the shifts in patterns of rising and falling air cause the circulations to largely cancel each other out in the time-mean (top row of Figure 9).

Due to the stronger ENSO, interannual variation in tropical precipitation over the eastern equatorial Pacific is stronger in PANCAKE than in CONTROL (Figure 10); La Niña years are drier in PANCAKE than CONTROL (middle panel), El Niño years are wetter (bottom panel), and the mean changes are more subdued (top panel). However, the Maritime continent, including Indonesia and Papua New Guinea, is drier in both La Niña and El Niño years, and East Africa is wetter, consistent with the changes to the Walker circulation discussed above.

When mountains are present, convection is focused in the Maritime region and ENSO warm anomalies often only reach the central Pacific, whereas without mountains the Maritime region dries and ENSO warm anomalies consistently cross the entire Pacific basin (Figure 7). This suggests that Maritime orography might have a mooring effect on convection. Authors have highlighted two distinct mechanisms by which tropical orography influences monsoonal circulation by promoting convection: 1) mountains provide elevated heating surfaces and 2) mountains provide "lift" by forcing air up-slope (Meehl 1992; Kutzbach et al. 1993). In each case, convection leads to precipitation and the release of latent heat into the atmosphere, further fueling the convection. Although these authors stress the importance of these mechanisms in monsoon systems, these mechanisms should also be at work over the Maritime continent. The raised heated surfaces and orographic lift associated with Maritime orography may play an important role mooring convection over that region.

6. Mechanisms driving ENSO changes

PANCAKE's equatorial wind zone, between the latitudes of each hemisphere's strongest easterly winds, is significantly widened compared with CONTROL (Figure 11a). The wider equatorial wind zone in PANCAKE expands the off-equatorial region of upwelling related to Ekman suction, pushing the region of downwelling associated with Ekman pumping poleward in both the eastern and western Pacific (Figure 11b). The changes in wind stress curl in the western Pacific, including weaker positive winds stress curl from 5°-15°N, result in a increased shoaling of the thermocline into the North Equatorial Countercurrent and a slightly deeper Equatorial Undercurrent (Figure 11 c and d, left column), circulating colder waters to the east Pacific. Together, these changes result in a significantly colder east Pacific equatorial thermocline during La Niña years (Figure 11 c and d, right column).

Although the mean equatorial Pacific thermocline exhibits a shallower slope in PANCAKE relative to CONTROL (Figure 12, top), the changes to the surface winds discussed above result in a steeper thermocline slope during La Niña years (Figure 12, middle). The very strong warm ENSO events are associated with very significant shoaling of the thermocline in the western Pacific and a much deeper thermocline in the eastern Pacific (Figure 12, bottom). The mean thermocline is clearly influenced by the strong ENSO events. We interpret the steep La Niña thermocline as an important driver of the stronger ENSO warm events in the PANCAKE simulations (e.g., Fedorov and Philander 2001; Wittenberg 2002; Zelle et al. 2005; Vecchi and Wittenberg 2010). As with the Pacific Ocean, the much stronger changes in the slope of the Indian Ocean equatorial thermocline between PANCAKE La Niña and El Niño years relative to CONTROL is consistent with the much greater interannual variation in SST, wind stress and precipitation anomalies in both basins (Figure 7).

Strong ENSOs in AOGCMs have been associated with wind-thermocline coupling that dominates over wind-SST coupling, and there is evidence that the dominance of these types of feedbacks may explain the variation in types of ENSO warm events in nature (Guilyardi 2006; Merryfield 2006). Wind-thermocline driven ENSO events are characterized by anomalies in heat and thermocline depth that propagate from the western Pacific to the eastern Pacific, preceding SST and wind anomalies with a similar propagation. Our ESM2Mb experiment exhibits a strong wind-thermocline feedback in lag-regression plots, where anomalies in equatorial SST, zonal wind stress, zonal currents of the top 50 meters of water and the depth of the 20° isotherm are regressed onto Nino3 region SST anomalies (Figure 13). Warm Nino3 SST anomalies (Figure 13a) and westerly wind anomalies over the ocean (Figure 13b), associated with El Niño events, begin earlier and last longer in PANCAKE than in CONTROL, and progress from the Western Pacific to the Eastern Pacific. Anomalous eastward zonal currents of the top 50 meters of the equatorial Pacific (Figure 13c, red colors are eastward anomalies) begin earlier in PANCAKE than in CONTROL, and a relatively deep thermocline (Figure 13d) progresses from the Western Pacific to the Eastern Pacific, preceding the SST and wind stress anomalies. The colder cold-tongue in La Niña years leads to stronger SST anomalies and stronger wind stress anomalies. Together with the stronger wind stress anomalies associated with the colder cold-tongue and larger SST anomalies (Figures 12, 13), the enhanced wind-thermocline coupling and the steeper La Niña thermocline help to explain the larger amplitude ENSO events in PANCAKE Earth.

In a similar experiment where global mountain height was systematically varied using a coupled AOGCM (MRI-CGCM2) and ENSO changed in a qualitatively similar way to this study, the author concluded that the change in amplitude and frequency of ENSO was related to the expanded equatorial easterly wind region (Kitoh 2007). This conclusion followed previous studies that found that a larger meridional extent of ENSO-related wind anomalies results in a lower frequency and higher amplitude ENSO due to the fact that Rossby waves travel slower at higher latitude (Merryfield 2006; Capotondi et al. 2006). In our experiment, although we find that our equatorial wind region expands poleward, the latitudinal range of ENSO-related wind anomalies does not change significantly (Figure 14). We interpret the decrease in frequency of PANCAKE as the result of the consistently larger longitudinal span of ENSO warm events and wind stress anomalies that are further East in the Pacific basin (Figure 14), which in turn we associate with the lack of convective mooring by Maritime orography.

7. Conclusions

We performed a classic idealized experiment using state-of-the-art Earth System Models to explore the impact of mountains on Earth's climate system. Our simulations exhibited similar characteristics to previous studies including more zonal winds and weaker monsoons when land-surface topography is removed. However, we also found broad changes to tropical circulation patterns, impacting the mean climate and interannual variability. Without orography, convection over the Maritime continent is weakened and precipitation is not as moored to the West Pacific Warm Pool; it spreads out over the Indian Ocean and East Africa. Changes in convection and surface winds due to the removal of mountains have a strong influence on equatorial atmosphere-ocean dynamics, leading to a more regular ENSO with a lower frequency and much stronger amplitude. The large changes to ENSO result in a mean Pacific Walker circulation that is ~44% weaker, and much larger interannual variation in tropical precipitation and global net radiation at the top of the atmosphere. These results are consistent across the two models used in this study, and are qualitatively similar to the results of a previous study that used a non-related AOGCM (Kitoh 2007), suggesting that these conclusions are robust.

How have changes to Earth's orography over the last few million years influenced ENSO and the Walker circulation, and what were the impacts on East African, tropical, and global climate? Although we speculate that changes in Maritime orography may have had a strong influence on climate dynamics over the last few million years, our study cannot constrain the role of specific orography in the changes we found, and did not attempt to examine a realistic paleo-orographic scenario. Future work should address the influence of particular orography, especially in the area of the West Pacific Warm Pool, on ENSO, the Walker circulation, and regional to global climate.

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Figure Captions

Figure 1. Land topography and ocean bathymetry (meters) in CONTROL model (top) and PANCAKE model (bottom). In PANCAKE, all land surface topography, including ice height, was removed from the ESM2Mb and ESM2G land models for these experiments.

Figure 2. Differences (PANCAKE – CONTROL) of 100-year means (years 401-500) for precipitation (top), pressure velocity ω (middle), and sea-surface temperature (bottom). All values are from ESM2Mb. Values for ω are from 500 hPa. Negative (blue) values are in the "up" direction. Results for ω do not change significantly when different pressure levels, or an average of pressure levels, are used to represent the middle of the troposphere. Black rectangles show regions used to calculate dSLP as the difference between average sea-level pressures in an equatorial region of the east Pacific (140°W-80°W, 5°S-5°N) and the west Pacific (120°E-180°E, 5°S:5°N).

Figure 3. Walker and Hadley circulations. The Pacific Walker circulation weakens in PANCAKE, whereas the strength of the Hadley circulation remains largely unchanged. Pressure velocities are shaded (blue/negative values are in the up direction) and vectors are zonal wind (***u***) and vertical wind (**w**) for Walker circulation (left column; values are meridional averages from 5°S-5°N) and meridional wind (***v***) and vertical wind (**w**) for Hadley Circulation (right column; values are zonal averages). **a** Schematic depiction of Walker (left) and Hadley (right) circulations. **b** ERA-INTERIM Reanalysis data from Jan 1981-Dec 2010. **c** ESM2Mb CONTROL. **d** ESM2Mb PANCAKE. Grey curve on each

plot near the abscissa shows approximate topography from observations (**b** from etopo40) and the respective models. The vertical component of the wind speed vector (**w**) was approximated from the pressure velocities using the relationship w= ω/(-ρg), where ρ is density and g is gravitational acceleration, and are scaled x1000. Note the different color scales for the left and right sides of the figure.

Figure 4. Changes in tropical mean atmospheric overturning circulation and the hydrologic cycle. PANCAKE experiments (black points) exhibit the relationship between changes in average surface temperature (TS) and fractional changes to column-integrated water vapor (q) and precipitation (P) expected [*Held and Soden*, 2006] similar to modeling experiments forced with Last Glacial Maximum (blue points) and 2xCO2 (red points) conditions (a and b). However, fractional changes in the total average upward component of ω in the middle of the troposphere (500mb) are decoupled from estimated fractional changes to atmospheric convection (ΔP/P-7.5ΔT [*Held and Soden*, 2006]) in the PANCAKE experiments (c), yet continue to be correlated with changes to dSLP, a measure of the strength of the Pacific Walker circulation (d). The PANCAKE experiments exhibit a larger weakening of the Walker circulation and a larger change to fractional upward ω at 500mb than the any of the 2xCO2 experiments. Last Glacial Maximum (blue points) and 2xCO2 (red points) from [*DiNezio et al.*, 2011].

Figure 5. Nino3 region (150°W-90°W, 5°S-5°N) SST spectra for ESM2Mb (left) and ESM2G (right) calculated for model years 101-500. Abscissa units are °C^2/octave. Based on previous work with a closely related model that reported the spread along the abscissa

between multiple spectra generated from time-averaging over various time intervals [*Wittenberg*, 2009], we estimate that time-averaging over four centuries limits the spread to <1 °C^2/octave, much less than the difference between the CONTROL and PANCAKE spectra for a given time frequency in both models.

Figure 6. a) Southern Oscillation Index (SOI), b) Nino3 SST anomaly (°C), c) tropical precipitation anomaly (mm/day, averaged over 20°S:20°N), and d) global net radiation at the top-of-the-atmosphere anomaly (W/m^2, positive values correspond to downward flux) from ERA-20c reanalysis (left) ESM2Mb CONTROL (middle) and ESM2Mb PANCAKE (right). The SOI is calculated from the sea-level pressure difference between Darwin (130°E, 12°S) and Tahiti (150°W, 17°S). Sea-surface temperature anomalies are monthly anomalies from the Nino3 region (150°W-90°W, 5°S-5°N) calculated using a running 211-month triangular smoother. Blue colors indicate La Niña years and red colors indicate El Niño years. The ten El Niño and ten La Niña years that were chosen for analysis in this paper are bracketed by their corresponding colors. The vertical scale is the same for all plots. Tropical precipitation is average from all longitudes and from 20°S – 20°N. Abscissa shows the calendar year (for ERA-20c) or the model years.

Figure 7. Longitude-time plot of three-month running anomalies relative to mean climate averaged over 5°S-5°N for (a) SST (°C), (b) zonal wind stress over the ocean (middle, hPa) and (c) precipitation (bottom, mm/day) from ERA-20c reanalysis (left, years 1980-1999), ESM2Mb CONTROL (middle, model years 481-500) and ESM2Mb PANCAKE (right, model years 481-500). Time increases in the vertical direction. Longitudes cover

the Indian and Pacific Ocean basins. Approximate location of Indonesia is show below the abscissa.

Figure 8. Distribution of monthly oceanic zonal wind stress anomalies (a) in the Nino4 region (160°E-150°W, 5°S-5°N) and SSTs (b) in the Nino3 region (150°W-90°W, 5°S-5°N) for ESM2Mb CONTROL (left) and ESM2Mb PANCAKE (right), model years 401-500. The zero anomaly line is shown. Note the difference in scale of the y-axis between CONTROL and PANCAKE plots.

Figure 9. Average vertical wind velocities (hPa) between 5°N-5°S for model years 401-500 (top), ten La Niña (middle) and ten El Niño (bottom) from ESM2Mb CONTROL (left) and ESM2Mb PANCAKE (right). Spatial changes to the equatorial Walker circulation on interannual timescales in the PANCAKE simulations is partially responsible for the weakening of the circulation in the time-mean. Blue color indicates rising motion; red color indicates subsidence.

Figure 10. Precipitation difference (ESM2Mb PANCAKE minus CONTROL) for the model years 401-500 (top), ten La Niña years (middle) and ten El Niño years (bottom). PANCAKE has less precipitation over the Maritime continent and over the east equatorial Atlantic/west equatorial Africa, and more precipitation over eastern equatorial Africa in all years, indicating that these patterns are not the result of the large changes to ENSO.

Figure 11. (a) Zonal wind stress on the ocean (Pa), positive wind stress is westerly; (b) Wind stress curl (N/m^3) scaled by a factor of 10^8; (c) ESM2Mb CONTROL ocean temperature and zonal currents; (d) ESM2Mb PANCAKE ocean temperature and zonal currents. All data is for ten La Niña years; left column panels are averaged over the Eastern Pacific (150°E-150°W) and the right column panels are averaged over the Western Pacific (150°W-80°W). In the bottom four panels Ocean temperature (°C) is shaded and zonal current is contoured. Solid contours indicate eastward movement (out of the page). The Equatorial Undercurrent corresponds to the solid contours below the surface centered at around 0° latitude in both the Eastern and Eastern Pacific. The North Equatorial Countercurrent corresponds to the solid contours in the Western Pacific (left) between 5°-10°N. The blue contour in the bottom four panels shows the 20°C isotherm.

Figure 12. Average depth (meters, 5°S-5°N) of the 20° isotherm in the equatorial Indian and Pacific basins. One-hundred year mean from model years 401-500 (top), ten La Niña years (middle) and ten El Niño years (bottom), for CONTROL (black) and ESM2Mb PANCAKE (red). Approximate location of Indonesia is indicated below the abscissa.

Figure 13. Equatorial variable anomalies averaged between 2°S-2°N and lag-regressed onto Nino3 SST anomalies, spanning two years before (negative lag months) to two years after (positive lag months) the peak Nino3 SST (warm) anomalies (zero-line). ENSO in ESM2Mb exhibits a strong wind-thermocline coupling. ESM2Mb CONTROL (top) and ESM2Mb PANCAKE (bottom). Vertical lines where data is absent correspond to

Indonesia, where Borneo and Sumatra occupy regions expanding the entire 4° latitude shown here.

Figure 14. SST (left, °C) and zonal wind stress over the ocean (right, kPa) regressed on Nino3 region (150°W-90°W, 5°S-5°N) SST anomalies for ERA-20c (top), ESM2Mb CONTROL (middle) and ESM2Mb PANCAKE (bottom).